COVER SHEET

EVALUATION OF RAPID TOOLING FOR ELECTRIC DISCHARGE MACHINING USING ELECTROFORMING AND SPRAY METAL DEPOSITION TECHNIQUES

Ricky Blom, Prasad KDV Yarlagadda and R. M. Iyer
School of Mechanical, Manufacturing and Medical Engineering
Queensland University of Technology
Brisbane, Q 4001, Australia
E-Mail: y.prasad@qut.edu.au

ABSTRACT

Electroforming and spray-metal deposition offer an alternate option to traditional machining of electrodes. Electroforming is one method of producing electrodes for EDM. The fact that electroforming can be used to produce multiple electrodes simultaneously gives it the advantage of saving on costs when multiple electrodes are needed. Spray-metal deposition offers another alternative that is much cheaper and relatively faster to manufacture. In this paper the use of these non-traditional manufacturing methods are compared to the performance of traditional solid electrodes in terms of machining time, material removal rate, tool wear rates and surface roughness at several standard machining settings.

1. INTRODUCTION

To compete in today's industry environment, companies must keep up with the leading technologies and processes and also push the boundaries and develop new and improved products and processes. The Manufacturing Industry is an area where time, efficiency and accuracy are the major driving forces behind innovation and research. The most competitive companies are those who continually reduce process times, increase efficiency and improve accuracy. Rapid Prototyping and Tooling is an area that has and is continuing to reduce production time and increase efficiency and accuracy in developing and manufacturing prototypes compared to traditional prototype manufacture.

Electro-Discharge Machining (EDM) is a manufacturing process that has been affected by developments in Rapid Prototyping and Tooling. EDM is commonly used by toolmakers for complex injection moulds, punch dies and cavities made from hardened tool steels. EDM is ideal for materials and complex shapes that traditional machining processes are unable to perform. In die and mould production, the EDM cycle can account for 25 to 40% of the tool room lead-time [1, 2]. The electrode production represents over 50% of the cost and time of an EDM operation [2]. The goal is to reduce the time and cost of the EDM cycle and to do this, alternate methods of electrode production is a key area of research. Since conception EDM electrodes have been manufactured from solid conductive metals including copper and tungsten, and also from non-metals mainly graphite. Using traditional machining operations in producing complex electrodes from solid copper or graphite may require the production of several smaller electrodes and joining them together, or running several machining cycles to get the required cavity or shape. Therefore increasing the complexity of the electrode increases the electrode production time and also increases the machining time if several machining cycles are required. In this paper attempts made by the authors in investigating the alternate methods of electrode production in order to reduce cost and time are presented.

2. LITERATURE REVIEW AND BACKGROUND

Rapid Prototyping (RP) and tooling is a continuation from three-dimensional CAD modelling. RP uses the CAD data to produce layer information that is feed into RP machines to produce a three dimensional solid model from a chosen process and material. Common RP processes include Stereolithography (SL), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM) and Fused Deposition Modelling (FDM). The majority of RP processes involve the conversion of the CAD data into cross-sectional information and the model is built layer-by-layer. In the production of EDM electrodes many RP processes have been previously used. The most promising process involves the use of stereolithography and producing models as either positive or negative master patterns. Stereolithography (SL) uses information from a computer generated three-dimensional model to produce a solid three-dimensional model from various types of laser-curing polymer resins. The Stereolithography Apparatus builds the three-dimensional solid model layer by layer. The computer file is broken down to layers and the SLA reproduces the layer on the surface of the resin. The part is then lowered by the relative layer thickness, and the process is repeated until the completed model is produced. The Stereolithography Apparatus used is developed and marketed by 3D Systems Inc, Valencia, California, USA. The machines produce models with high detail and accuracy and have the ability to produce multiple parts simultaneously. Using the positive master pattern is termed as "Direct Electrode Manufacture" in that the SL pattern is plated with a conductive material and used as the electrode. Alternatively, using the SL pattern as a negative and removing the plated shell is termed as "Indirect Electrode Manufacture".

Research in the area of Direct Electrode Manufacturing process includes work from Arthur et al. [3-7] and Leu et al. [8]. Results using the direct manufacturing method have shown advantages in that the electrodes are comparable to traditional solid electrodes in finishing, semi-roughing and roughing machine settings and electrode production time is reduced as large quantities of electrodes can be produced simultaneously. The results also concluded disadvantages including the possibility of non-uniform distribution of electrodeposited material resulting in unknown plating thickness, EDM machining time is quite high, the SL master pattern is sacrificial and the electrodes are prone to premature failure if the plating thickness is less than 180 μm. Alternatively the area of Indirect Electrode Manufacture has been researched and developed by Jensen and Hovtun [9], Rennie et al. [10] and Yarlagadda et al. [11,12.13]. Advantages for using indirect electrode manufacture include relatively low manufacturing cost, multiple electrodes can be produced simultaneously, the master pattern can be reused multiple times and the electrodes can be manufactured to high accuracy and quality. Jensen and Hovtun were also able to show that the performance is comparable to solid electrodes. Jensen and Hovtun [9] found disadvantages that include unacceptably high wear rate, poor accuracy, long process time and internal details can be problematic. Rennie et al. [10] provided similar disadvantages in that narrow internal cavities are not plated to the same thickness as external features and failure still occurs with excess wear and uneven material distribution. Yarlagadda et al. indicated that different sections of the tool performed more work than other sections, triangular protrusions had split and tool failure occurred and course machining can deform the tool. In this proposed experimental study the following stepwise procedure has been followed.

- Development of CAD models of Electrodes
- Rapid prototyping and tooling to produce electrode mater patterns,
- Electroforming negative tool to produce copper shells for electrodes, and backfilling to give the shell support,
- Machining of Solid Copper Electrodes for comparison to alternatively produced electrodes,
- Production of Spray-metal copper shells for electrodes,
- Testing Electrodes comparing MRR, TWR and Surface finish for the different production methods,
- And evaluating results and developing conclusions.

3. EXPERIMENTAL DESIGN

The experiments in this research are based on a similar procedure to Leu et al. [8]. The procedure allows an indication of the difference in the performance of different manufacturing methods. Leu et al. [8] provided a comparison between electroformed copper electrodes and traditional solid electrodes by running experiments at three different machine settings for a set time of ten minutes. There were a total of eight experiments per electrode type at each machine setting. EDM performance is dictated by the machine parameters and the optimisation of those parameters has been the basis of research by the majority of research groups in the field of EDM. Due to time and budget restrictions the number of experiments determined the type of analysis that could be done. The Taguchi method and neural network experiments require a large number of experiments to prove the methods and the budget didn't allow that size research. Leu et al. [8] completed eight experiments per machine setting for each electrode type and to get results that are comparable, within the budget, only two experiments for each machine setting and electrode type were conducted. A comparison of the three electrodes (solid copper, electroformed copper and spray metal copper) will be made using the same machining conditions and measuring the performance attributes. The performance attributes measured include material removal rate (MRR), tool wear ratio (TWR) and surface roughness (R_a). The electrodes will be tested under three machining conditions and measured to compare the performance attributes. The machining conditions include a roughing cut, semi-roughing cut and a finishing cut. Using the same machine parameters for all three electrodes will allow a good comparison to be made. The settings for the three different experiments involve the following parameter settings

Table 1 Machine Settings or Finishing, Semi-Roughing and Roughing Cuts

Machine Setting	Discharge Pulse Duration **ON**	Quiescent Pulse Duration **OFF**	Quiescent Time **MA**	Peak Current **IP**	Servo Voltage **SV**	Polarity **PL**
C110	012	012	01	002.0	03	+
C140	016	016	01	005.0	05	+
C170	019	019	01	010.0	05	+

The values given are not actual values. They are machine setting numbers for the scale on the machine. The actual values for the machine settings are as follows:

Table. 2 Actual Settings or Finishing, Semi-Roughing and Roughing Cuts

Machine Setting	Discharge Pulse Duration **ON**	Quiescent Pulse Duration **OFF**	Quiescent Time **MA**	Peak Current **IP**	Servo Voltage **SV**	Polarity **PL**
C110	80μsec	20μsec	X2	2A	35V	+
C140	180μsec	20μsec	X2	5A	60V	+
C170	350μsec	30μsec	X2	10A	60V	+

To restrict the experimental machining time the cut depth will be reduced according to the cut type. The roughing cut will make a cut of approximately 1mm, the semi-roughing cut will be 1mm and the finishing cut will be 0.5mm. The machining time is measured on the EDM computer control unit and it measures to an accuracy of seconds. The electrodes and work-pieces will be measured before and after to determine the MRR, TWR and R_a. The MRR can be measured using a mathematical equation –

$$MRR\left(mm^3 / hr\right)=\frac{Electrode\ Area\left(mm^2\right)\times Depth\ of\ Cut\left(mm\right)}{Time\ of\ Cut\left(\min\right)} \tag{1}$$

MRR can also be measured by the change in weight of the electrode and the work-piece. The mass of the electrodes and work pieces was measured on standard electronic scales which measures masses from 0 to 100g to an accuracy of 0.001g increments, masses from 100 to 500g to 0.01g increments and above 500g to 0.1g increments.

The TWR is measured by –

$$TWR\left(\%\right)=\frac{\Delta Volume^{Electrode}\left(mm^3\right)}{\Delta Volume^{workpiece}\left(mm^3\right)}\times 100 \tag{2}$$

The measurements can be made by weight and also the use of a coordinate measuring machine (CMM). CMM was chosen because of the accuracy attainable and also the availability of the machine itself. The CMM has the accuracy to measure down to 0.001mm in horizontal axis and vertical axis. The CMM is used to measure the vertical height and change of height at preset coordinates in the horizontal plane (x axis and y axis). Using the CMM, a grid is used to measure preset points before and after experiments. The difference is used to determine the amount of wear or material removed from different sections and features of the electrodes and test pieces. The R_a is measured using a machine such as a Taylor Hobson Surtronic instrument. Several measurements are made on each electrode and test piece to give and average roughness of the whole machined surfaces. The surface roughness is measured to the very fine increments of 0.01μm. The measuring probe scans a 4mm section of the surface and then determines the average surface roughness (R_a). Measurements for the experiments were made on equipment available but the measurements such as the masses, volumes and heights could have been measured to greater accuracy with more advanced machines. The volume is one method that was unable to be used but if a three dimensional scanner was available it would have been possible to measure the change of volume.

4. EXPERIMENTAL PROCEDURE AND RESULTS

The experimental results compare the performance of the different electrode manufacturing methods at the three different machine settings. The aim is to compare the electrode performance at different workloads on the electrode from roughing cuts, semi-roughing and finishing cuts. The three settings cut at different speeds so the depth of cut for the finishing cut was reduced. This was to prevent the machining time from climbing too high. The selection of electrode shapes (Figure 1) was to help compare different areas of tool performance. The three shapes used highlighted smooth curved surfaces, sharp corners, low draft angles and complex deep holes. The Electrodes were all set up in the same conditions and the similar shapes made the same cuts at the same settings. The depth of cut is measured from the top surface of the work piece and the experiments begin with the depth of the hole in the near net casting. The first four experiments are 1mm cut added to the previous measurement and the final two experiments are 0.5mm extra.

Figure 1 – SLA Electrode Master Patterns

The electrodes and work pieces were measured before and after each experiment to determine the MMR, TWR and R_a. A total of six experiments were carried out. Due to manufacturing costs two sets of three solid copper electrodes, six sets of three electroformed electrodes and two sets of three spray metal electrodes were produced. Due to the porosity and uneven thickness in the spray metal electrode shells the backing material penetrated and made the electrodes unusable. The experimental conditions for a roughing cut used in the first set of experiments with the machine set on a standard machine setting of C170. This produced high MRR and R_a with low machining time and TWR. The machine and actual settings used for one of these studies are as follows:

	Nominal	Actual
Machine Setting:	C170	C170
Discharge Pulse Duration (ON):	019	350µsec
Quiescent Pulse Duration (OFF):	019	30µsec
Quiescent Time (MA):	01	X2
Peak Current (IP):	010.0	10A
Servo Voltage (SV):	05	60V
Polarity (PL):	+	+

The following is the depth of cut for the first set of experiments:
Cone Electrode – 28mm

Triangle Electrode – 26mm
Base Electrode – 19mm

4.1 Damage and excessive wear of Electroformed Base Electrode (EB1)

The cone electrodes show similar characteristics as the base electrodes in that the solid electrode has less than 0.1mm wear and the electroformed electrode shows greater wear of over 0.1mm on the higher sections. The negative wear on the electroformed electrodes was caused by the deformation of the electrode. Heat from the EDM process builds up in the copper and is partially insulated by the back filled material therefore expanding the copper. Increased localised wear on the point of the electrode is also caused by the extra work performed by the tip. The work piece is a near net casting and the cavity has more material to remove at the base of the cavity until the hole is identical to the electrode shape. The CMM results for the solid cone electrode shows a negative wear in a small area near the front left of figure 2. The negative wear is the result of a carbon build up from an inclusion in the work piece casting. Figure 3 shows the inclusion that appeared after the first experiment and the black carbon build up on the electrode. The inclusion didn't appear to affect the MRR.

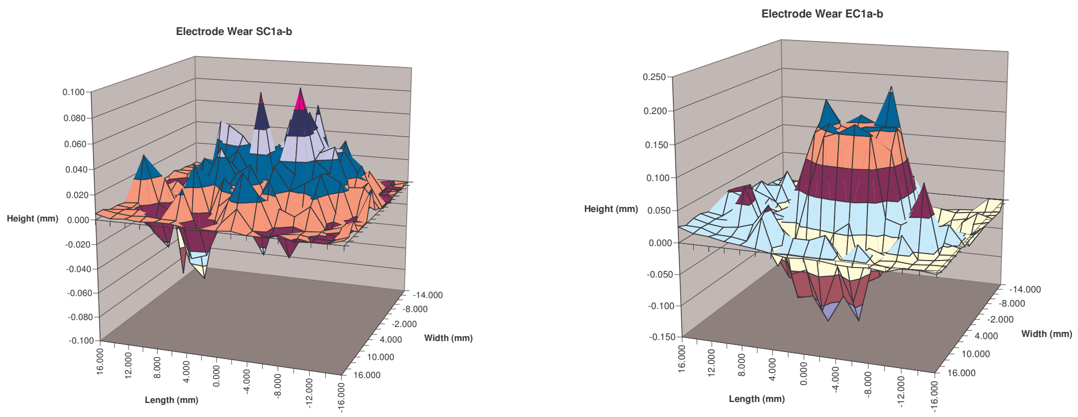
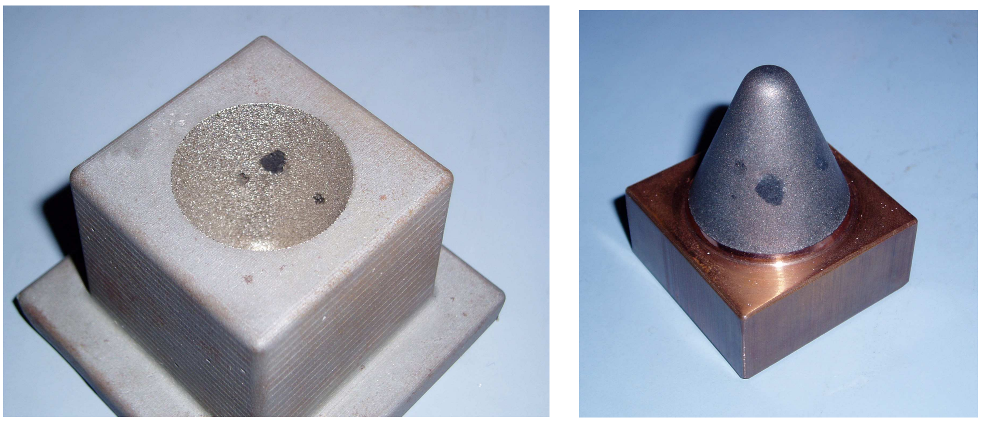


Figure 2 Cone Electrode Wear Experiment 1 - Solid Electrode and Electroformed Electrode


(a) Work piece (b) Electrode
Figure 3 Casting Inclusion and Electrode Wear

Triangle electrodes gave a very good indication of excessive wear when the electrode is needed to machine larger amounts of material. As shown in Figure 5.5 the solid electrode has lower wear than the electroformed electrode. The higher wear along two sides of the electrodes was produced by increased work rate. The cavity of the near net castings is slightly smaller than the electrodes and any vertical surfaces will be machined more than the surfaces that are more horizontal. From the current experimental investigation it can be stated that the solid triangle electrode performed better than the electroformed electrode in terms of the shape of the machined cut, because the electroformed electrode failed during the experiment. The sharp corners of the electrode wore through to expose the back filled core and therefore stopped machining in that small area.

4.2 Performance Comparison of Manufacturing Methods

The machine settings for the three levels of machining as shown in Table 2 show that as the machining goes from C170 (roughing) down to C110 (finishing) the Pulse ON and OFF drops as does the Peak Current and Servo Voltage. As the parameters drop the machining time should increase, the MRR should decrease, the TWR should increase and the R_a should reduce. As the experiments in this work have shown that the results followed the expected trends in that the machining time increased, the MRR decreased and the Ra decreased. The TWR measured as expected for the electroformed electrodes but the solid electrodes performed against the expected trend.

5. CONCLUSIONS

Manufacture of three different shapes of electrodes in three different manufacturing methods was achieved. The solid copper and electroformed copper electrodes were manufactured successfully to the experimental stage however the spray metal electrodes were unusable. The experiments with the solid electrodes and electroformed electrodes were conducted with success at three different machines setting and comparisons were able to be made. The solid electrodes consistently performed better than the electroformed electrodes at all machine settings in Machining Time, MRR and TWR. Although the solid electrode has out performed the electroformed electrodes in the majority of the experiments, the solid electrodes are much more expensive to produce. The standard workshop is more likely to have a machining centre to machine solid electrodes as opposed to an electroplating system to produce electroformed electrodes so the convenience of the solid electrodes will often out way the use of electroformed electrodes.

The cost of electrodes becomes a major factor as soon as the electrode manufacturing process becomes more comparable. Even though the solid electrodes out performed the electroformed and spray metal electrodes, the cost of manufacture plays a vital role in the tooling process. This research has shown that the cost of solid electrodes is $810 each which is six times that of electroformed and spray metal electrodes at $130 each. Solid electrodes take approximately six hours to produce where as a single electroformed electrode will take up to 50 hours to produce. The cost of production is sometimes not the critical factor when rapid tooling is required. For low numbers of electrodes it is probably more economical in terms of time to use traditional machining. However when a large number of electrodes are required, electroforming will take a similar amount of time to produce one electrode as it will take to produce an infinite number of electrodes and therefore becoming faster as long as more than 10 electrodes are required. The electroforming process could be a viable option for the EDM process if the electrodes could be produced more robust and consistent shell thickness. Problems with the shell thickness produced warping and delamination on some of the larger flat surfaces. With greater control over the wall thickness and greater heat conductivity of the backing material would give better performance of the electroformed electrodes.

REFERENCES

1. .Semon, G., *A Practical Guide to Electro-Discharge Machining.* 1975: p. 63-76.
2. Jacobs, P.F. *Rapid Prototyping and Manufacturing*. in *SME*. 1992. Dearborn USA.
3. Arthur, A. and P.M. Dickens. *Rapid Prototyping of EDM Electrodes by Stereolithography*. in *International Symposium for Electromachining*. 1995. Lausanne, Switzerland.
4. Arthur, A. and P.M. Dickens. *Material Removal & Tool Wear Rates In EDM With Stereolithography Electrodes*. in *5th Annual European Conference on Rapid Prototyping*. 1996.
5. Arthur, A. and P.M. Dickens. *Model EDM Electrodes As An Alternative Route To Complex Mould And Die Cavities*. in *6th European Conference of Rapid Prototyping*. 1997. UK.
6. Arthur, A. and P.M. Dickens, *Measurement of heat distribution in stereolithography electrodes during electro-discharge machining.* International Journal of Production Research, 1998. **36**(9): p. 2451-2461.
7. Arthur, A., P.M. Dickens, and R.C. Cobb, *Using rapid prototyping to produce electrical discharge machining electrodes.* Rapid Prototyping Journal, 1996. **2**(1): p. 4-12.
8. Leu, M.C., B. Yang, and W. Yao, *Feasibility study of EDM tooling using metalized stereolithography models.* Technical Paper - Society of Manufacturing Engineers. MR, 1998.
9. Jensen, K.L. and R. Hovtun. *Making Electrodes For EDM With Rapid Prototyping*. in *2nd European Conference of Rapid Prototyping*. 1993. University of Nottingham.

10. Rennie, A.E.W., C.E. Bocking, and G.R. Bennett, *Electroforming of rapid prototyping mandrels for electro-discharge machining electrodes.* Journal of Materials Processing Technology, 2001. **110**(2): p. 186-196.
11. Yarlagadda, P.K.D.V., et al. *Production Of Electro-Discharge Machining Electrodes By Using Stereolithography and Electroforming Process*. in *7th Annual European Conference of Rapid Prototyping*. 1998.
12. Yarlagadda, P.K.D.V., P. Christodoulou, and V.S. Subramanian, *Feasibility studies on the production of electro-discharge machining electrodes with rapid prototyping and the electroforming process.* Journal of Materials Processing Technology, 1999. **89-90**: p. 231-237.
13. Yarlagadda, P.K.D.V., I.P. Ilyas, and P. Christodoulou, *Development of rapid tooling for sheet metal drawing using nickel electroforming and stereolithography processes.* Journal of Materials Processing Technology, 2001. **111**(1-3): p. 286-294.